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Design and Verification of a Virtual Drive Test Methodology for Vehicular LTE-A Applications

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***Abstract*— In this paper, a Virtual Drive Test (VDT) emulation methodology for Vehicle to Infrastructure (V2I) Long Term Evolution–Advanced (LTE-A) communications is proposed, evaluated and compared against a traditional drive test approach. A generic antenna and radio test process is developed based on three-dimensional (3D) ray traced channel models, theoretic and measured antenna patterns, Radio Frequency (RF) channel emulation and Hardware In the Loop (HIL) radio measurements. The spatial and temporal multipath components of the radio propagation channel between the Multiple-Input and Multiple-Output (MIMO) enabled LTE-A Base Stations (BS) and the vehicle under test are accurately modeled for a site-specific virtual environment. Measured BS and LTE-A vehicular antenna patterns are incorporated into the system via spatial and polarimetric convolution with the synthetic ray data. The resulting channels are streamed into a wideband channel emulator that connects a multi-channel LTE-A BS emulator to a smart-phone representing the vehicular On-Board-Unit (OBU). The laboratory based LTE-A HIL system is used to study the handover process between two serving LTE-A BSs according to the received RF powers at the vehicular OBU. Emulated RF powers and data throughputs are compared with data from a traditional drive test to verify the legitimacy of the proposed methodology. Our VDT results in terms of Reference Signal Received Power (RSRP) and Physical Downlink Shared Channel (PDSCH) throughput match well the real-world LTE-A measurements for Single-Input and Single-Output (SISO) and MIMO operation. This new process benefits from being repeatable and via the use of ray tracing scales to support a wide range of urban and rural operating environments.**

***Index Terms*— LTE-A, MIMO, V2I, Handover, Channel Emulation, Ray Tracing, Channel Models, Vehicular Communication.**

I. Introduction

To meet the demands of modern vehicular applications, future communication networks require a consistent (and suitably high) data rate together with a minimum level of latency. These services must be delivered in a wide range of dynamic environments. Accurate propagation, antenna and vehicular channel modeling is required to meet these demands. It is expected that vehicles will communicate with other vehicles as well as infrastructure [1] using a number of different wireless technologies, including IEEE 802.11p/ITS-G5/DSRC [2, 3], Long Term Evolution – Advanced (LTE-A) [4] and (in the future) mmWave communications [5]. LTE-A is already capable of providing high data rates to many mobile users. Like all cellular systems, it benefits from good coverage (especially in urban environments), a high penetration rate and support for high-speed mobility. LTE-A is particularly well suited to provide the high-bandwidth [6], QoS-sensitive requirements necessary for vehicular infotainment services [7], and significant low delay (under 100ms) in V2I applications [8].

To overcome the small-scale fading typically observed at a moving receiver, a robust wireless connection requires multiple antennas for diversity and/or MIMO operation. In the context of LTE-A, this results in the need to deploy between 2 and 4 vehicular antennas. The design, placement and testing of these vehicular antennas in a range of representative environments, such as urban, rural and highways requires significant manpower, time and cost. One solution to reduce this burden is the adoption of Virtual Drive Tests (VDT), which enables test and optimization of the On-Board Unit (OBU) and its vehicular antennas prior to the vehicle being constructed. VDT is shown to provide a reliable, cost efficient and repeatable alternative to physical drive tests. It allows different OBU antenna solutions to be evaluated prior to the availability of physical samples. It also allows performance to be analyzed rapidly and effectively in a wide range of differing propagation scenarios.

The main contribution of this paper is the development of a novel method of VDT for performance evaluation of LTE-A V2I applications. We develop a generic antenna and radio test process that integrates 3D ray traced channel models (based on site specific geographic databases), theoretic and measured antenna patterns, real-time RF channel emulation and base station (BS) and OBU laboratory measurements.

In addition, we reliably and accurately perform laboratory-based handovers between BS[1] adjacent sectors (intra-site) and

BS neighboring cell towers (inter-site). Therefore, as the virtual vehicle drives between cell sectors or across the boundary between two adjacent cells, the BS emulator was configured to perform a handover. The channel emulator supports the bi-directional signaling necessary for automated handover between adjacent sectors and BS cell sites.

II. Related Work

Currently there are two ways of conducting VDTs. The first approach makes use of Radio Frequency (RF) antenna and channel models along with a standard-specific PHY layer simulator. Vehicles can then be driven in the virtual world, with the site-specific channel model feeding the PHY layer simulator [9-11]. This approach excludes the target BS and OBU systems and hence lacks accuracy. The second approach makes use of Hardware In the Loop (HIL) to emulate the dynamic RF conditions between the BS and OBU. This approach has recently attracted great interest [12-14]. With the aid of an RF channel emulator, manufacturers can avoid unintended interference and test vehicular communication systems in a controlled and repeatable environment. In [15] real-word channels were measured using an RF scanner for playback in a channel emulator to verify the performance of an automotive Electronic Control Unit (ECU), however the RF scanner limited the fidelity of the playback channel.

In [16], ray tracing channels were replayed in a Multi-Probe Anechoic Chamber (MPAC) using channel emulators in order to achieve VDT. However, the MPAC setup is complex and fails to accurately represent the BS and OBU antenna characteristics. Furthermore, in [16] there are no reported comparisons with practical road tests at the high layers. In [17], ITU standard channels were created for a commercial channel emulator for 3.65 GHz Mobile WiMAX performance analysis; however no antenna patterns were considered in the channel model. In addition, industry-approved and standardized channel models do not capture the unique and specific conditions experience by a mobile device as it physically moves through a realistic environment.

The novel VDT process presented in this paper is validated through the use of traditional drive test measurements for an urban route in central Bristol. Most importantly, advanced antenna and city-scale RF models are used to generate the time dynamic and spatially consistent V2I channel data. Since MIMO performance is under study, the predicted radio channels takes the form of time varying channel matrices. Synthetic and/or measured BS and OBU antenna patterns are incorporated into the process via spatial and polarimetric convolution with the predicted channel multipath. The resulting channels are streamed into a wideband channel emulator, which was programmed to generate the RF channels between an LTE-A dual-BS emulator and a smart phone (the latter used to represent the vehicular OBU).

The remainder of this paper is organized as follows: Section III discusses the methodology of processing 3D ray-tracing channel data for use with a channel emulator. We also provide a comprehensive overview of the antenna radiation patterns employed in the RF emulations. In Section IV, the simulation parameter settings are discussed, together with the proposed configuration of the conductive system. Section V compares results from the site-specific laboratory virtual drive tests with data captured from corresponding real-world drive tests. Conclusions drawn from this work are presented in Section VI.

III. Channel Generation Process And Antenna Radiation Patterns

A. Overview of the Ray-tracing Tool and Methodology

The spatial and temporal multipath components of the radio propagation channel between an LTE-A BS and the vehicular OBU are modeled using the University of Bristol's 3D outdoor ray-tracing tool [18-20]. The ray engine identifies all significant ray paths that travel between the BS and OBU in 3D space, up to a cut-off received power threshold of -120 dBm. The database includes undulating terrain and 3D buildings and foliage; all represented at a spatial resolution of 10m. Fig. 1 illustrates a snapshot of the ray tracing implementation for an example point-to-point link along the selected drive test route within the geographical map for central Bristol.

Along the selected route, the riverside road is covered by trees and residential buildings. Buildings on the other side of the river also provide scattered paths between the BS to OBU. The rays are color-coded according to received power over a range from -120dBm to -85dBm at the vehicular OBU. The lightest (white) and darkest (black) colours refer to the strongest and weakest rays respectively. The ray-tracing deterministic model has been previously validated for cellular and microcellular applications where the BS is located above, and well below, rooftop level at frequencies of 800MHz.

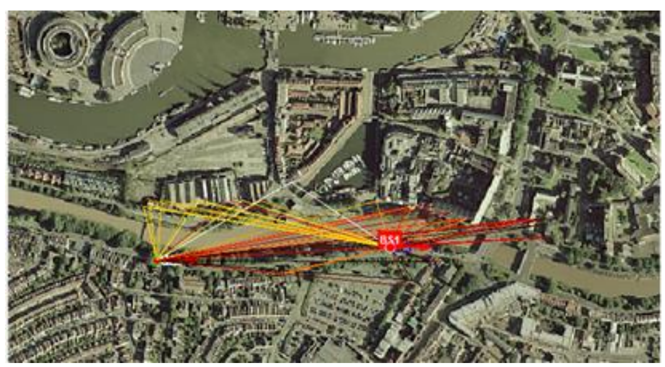

Fig. 1. Point to point ray-tracing and the resulting rays between BS and OBU.

The methodology follows the four-step process shown in the left-hand side of Fig. 2. The route selection task involves finding an appropriate drive route within the 3D virtual database. In this work, we use a 4km x 4km laser scanned database of central Bristol. A sample of this database, complete with a set of ray paths to an OBU, is shown in the right-hand side on Fig. 2. The RF channel generation process exploits the electromagnetic radio propagation characteristics of the surrounding environment (e.g. buildings, foliage and terrain). The impact of measured 3D polarimetric complex voltage BS and OBU antenna patterns is also incorporated via spatial and

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polarimetric convolution with the channel ray paths. The following subsection provides more details on the use of ray tracing in the channel generation step.

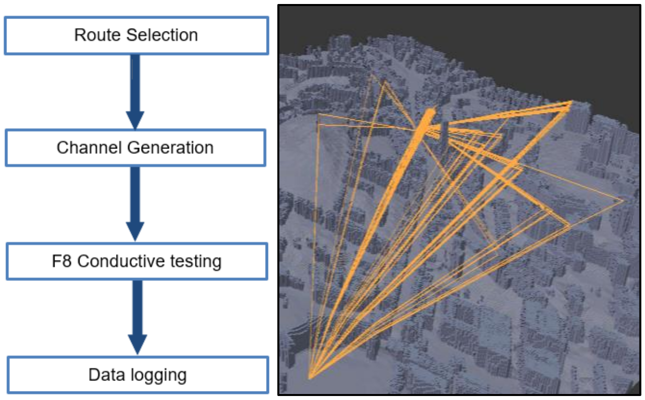

Fig. 2. Methodology flow diagram (left); Virtual 3D database and example ray structure (right).

B. Channel Modeling

In order to compute the set of wideband channel matrices suitable for LTE-A modeling, the procedure reported in [21] was followed. Point-source 3D ray tracing was performed from the BS to each of the vehicular OBU locations along the test route. This provides information on the amplitude, phase, time delay, 3D azimuth & elevation Angle of Departure (AoD) and Angle of Arrival (AoA) for each multipath component (MPC) linking the BS and OBU. The complex gain of each MPC was adjusted according to the transmitting (Tx) and receiving (Rx) antenna electric field (E) pattern responses for the correspond-ding AoD/AoA and polarization. The double-directional time-variant channel impulse response h for a link [22] is given by:

$$h(t,\tau,\Omega_{AoD},\Omega_{AoA}) = \sum_{l=1}^{L} h_l(t,\tau,\Omega_{AoD},\Omega_{AoA}) = \sum_{l=1}^{L} \mathrm{E_l}(t)\delta(\tau-\tau_l)\delta(\Omega_{AoD} - \Omega_{AoD,l})\delta(\Omega_{AoA}-\Omega_{AoA,l}) \quad (1)$$

where,

$$E_l(t) = \begin{bmatrix} E_{Tx}^{V} \\ E_{Tx}^{H} \end{bmatrix}^T \begin{bmatrix} a_l^{VV} e^{j\varphi_l^{VV}} & a_l^{VH} e^{j\varphi_l^{VH}} \\ a_l^{HV} e^{j\varphi_l^{HV}} & a_l^{HH} e^{j\varphi_l^{HH}} \end{bmatrix} \begin{bmatrix} E_{Rx}^{V} \\ E_{Rx}^{H} \end{bmatrix} e^{j2\pi v_l t} \quad (2)$$

In equation (1) $\delta(\cdot)$ represents the Dirac delta function, t is the variable of time, τ is the time-of-flight, $\Omega_{AoD}/\Omega_{AoA}$ represents the departure/arrival solid angle and L is the total number of MPCs. The l-th MPC has a double-directional time-variant channel impulse response h_l,, a complex amplitude $a_l^{XY} e^{j\varphi_l^{XY}}$ (a 2x2 matrix for all four polarization combinations), a time-of-flight τ_l, a Doppler frequency v_l and departure/arrival solid angles $\Omega_{AoD,l}/\Omega_{AoA,l}$. $E_{Tx}^{V/H}/E_{Rx}^{V/H}$ that represent the vertical and horizontal polarization components of the transmitting and receiving antenna electric field radiation patterns. The Doppler frequency shift v_l is given by [23]:

$$v_l = \frac{\|v\| \cos(\omega_{AoA,l} - \omega_v)\cos(\zeta_{AoA,l} - \zeta_v)}{\lambda} \quad (3)$$

where v represents the car velocity, $\omega_{AoA,l}$ is the azimuth AoA of the l^{th} MPC, $\zeta_{AoA,l}$ is the elevation AoA of the l-th MPC, ω_v is the car direction of travel in azimuth, ζ_v is the car direction of travel in elevation and λ is the carrier wavelength. In the system level simulations that follow, the time-variant nature of the channel is taken into consideration by providing updates after the transmission of each Orthogonal Frequency Division Multiplexing (OFDM) symbol. The time evolution of the channel is a function of the Doppler spread introduced by the vehicle motion.

The generated rays are assumed to be equivalent to the MPCs of the channel impulse response. Therefore, time binning was applied to the captured rays with a time resolution equal to the inverse of the signal bandwidth. The wideband channel frequency response $G(f) = [g_1, g_2, \ldots, g_N]$, where g_k represents the frequency domain channel for the k-th subcarrier, which was computed using a Discrete Fourier Transform (DFT):

$$G(f) = F\{h\}. \quad (4)$$

The channel model can be easily extended to support multiple antenna elements by accounting for the relative phase shift between each element with respect to a zero-phase reference point within the array, as shown in [24]:

$$e^{j\vec{k}\vec{d}} = e^{j\frac{2\pi}{\lambda}(x^0 sin\theta cos\phi + y^0 sin\theta sin\varphi + z^0 cos\theta)} \quad (5)$$

where x^0, y^0, z^0 is the position of the antenna element with respect to the zero-phase reference point at the receiving array (a similar assumption is made at the transmitting side), $\vec{k}$ is the wave vector and θ, ϕ are the elevation and azimuth angles in the spherical coordinate system of reference.

C. Antenna Radiation Patterns

Typical 3D polarimetric radiation patterns were used for both the BS and roof-mounted vehicular OBU antennas. The BS used a directional sector antenna with wide azimuth coverage and a narrow elevation beam, while the vehicular-based OBU antenna was more omnidirectional in nature and housed two antenna elements in a single shark-fin pod.

D. LTE-A BS Antenna

BS antenna data supplied by manufacturers generally includes information on azimuth and elevation half power beamwidth (HPBW), antenna overall gain and downtilt. Typical LTE 800MHz base stations use three antenna panels (120° rotated) with each having a typical gain of 16dBi and a downtilt in the region of 16°.

For the purposes of this paper, measured panel data for an 800MHz panel sector antenna with a gain of 16dBi was used. The quoted gain includes the power efficiency of the antenna [25]. Fig. 3(a) shows the measured far-field patterns for the 10° downtilted BS antenna in terms of its vertical and horizontal polarization components (45° slant) and the total power.

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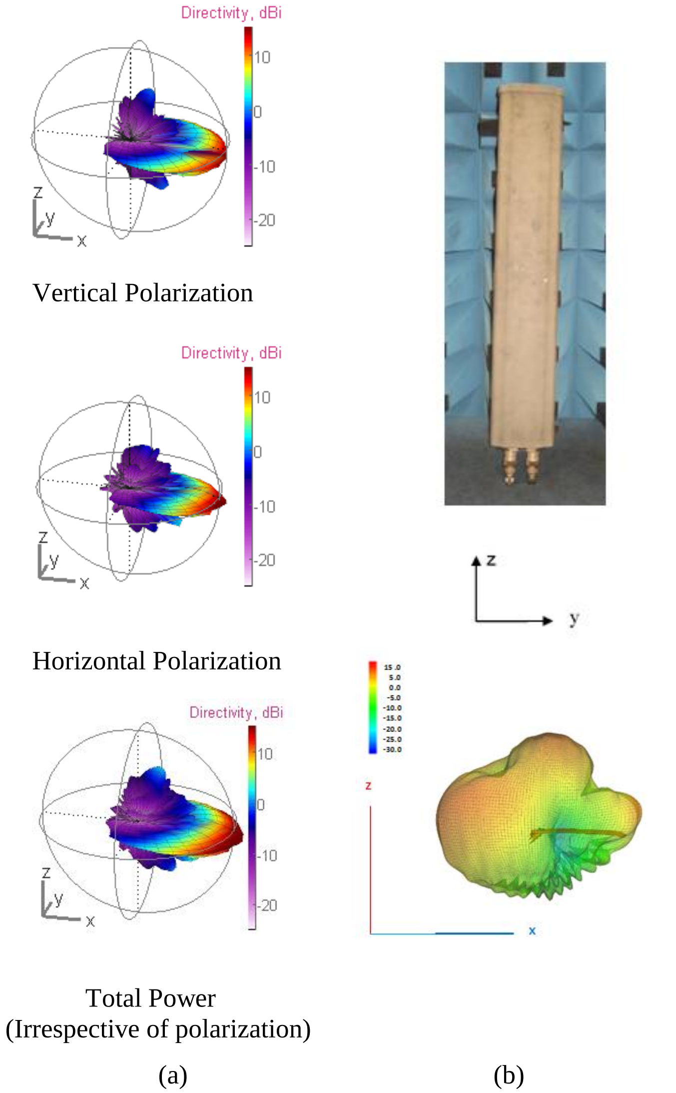

Fig. 3. (a) Measured BS radiation pattern data and BS panel antenna; (b) FEKO radiation pattern, antenna mounting and coordinate system.

E. *Vehicle antennas*

For the vehicular OBU, two antennas are housed in a single shark-fin pod (Fig. 4) located towards the rear of the vehicular rooftop. The antennas are denoted MIMO1 and MIMO2. As indicated in the right-hand side of Fig. 4, MIMO1 is located towards the rear of the pod, while MIMO2 is placed towards the front of the pod. The vehicle-based antenna patterns were generated using the FEKO [26] antenna simulation software. Fig. 3(b) shows the FEKO output for one of the antenna patterns and mounting. Fig. 5 shows the (embedded) patterns for both antennas in terms of polarization components and total power.

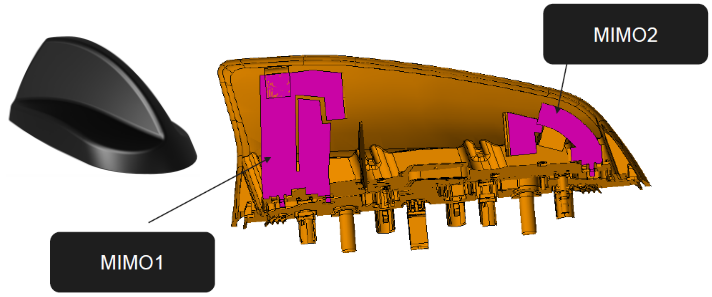

Fig. 4. MIMO vehicular antenna housed in shark fin pod.

MIMO2 has a more omnidirectional pattern and a maximum directivity of 8dBi, while MIMO1 has a directivity of 6dBi with its main beam directed towards the rear of the vehicle. For both antennas, vertical polarization is dominant, although there is still a reasonable amount of power (13% and 27%) in the horizontal polarization.

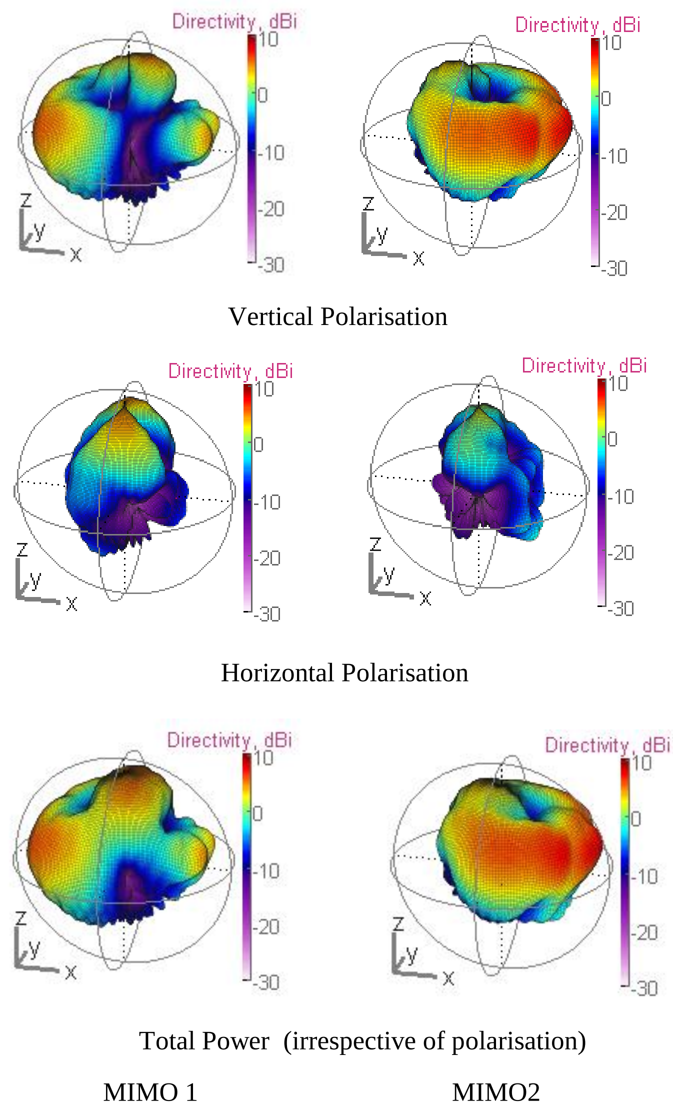

Fig. 5. Simulated radiation pattern data for vehicle antennas at 806MHz.

IV. Conductive Testing System Configuration

Conductive RF testing is a reliable and repeatable way of verifying the performance of an integrated OBU antenna system. The emulation of the radio connection from an LTE-A BS to an integrated OBU antenna system uses a combination of a Keysight F8 channel emulator along with the BS and OBU antenna patterns and channel multipath data from our city-scale ray models, as described in the previous sections.

A. System Configuration

By conducting the RF input/output from a dual-channel LTE-A BS emulator (in this case a Rhode and Schwarz CMW500 Wideband Radio Communication Tester) through our Keysight F8 channel emulator, it is possible to generate in real time the large-scale shadowing, delay spread and Rician K-factor, as well as the small scale multipath fading representative of the vehicular links observed as the test vehicle drives through the virtual city. The laboratory test bed configuration is shown in Fig. 6. Fig. 7 shows the RF conductive architecture for MIMO emulation. Additional circulators were required to separate the uplink and downlink during the emulation process.

The black lines in Fig. 7 indicate the uplink (UL) signaling paths, while the red lines indicate the downlink (DL) signaling paths. All connections were achieved using u.fl cables to ensure minimum loss. The OBU was represented using a commercially available Samsung S5 mobile phone, however modifications were performed to bring out the antenna connectors, thus allowing the phone to be connected to an on-car antenna system. In the laboratory tests, the Samsung S5 antennas were by-passed using SMA cables, and hence there was no need to place the phone in an RF shielded box. In the emulator, the BS and OBU rooftop antennas are embedded into the RF channels prior to streaming the data into the F8 emulator. Additional equipment (i.e., attenuators, circulators and splitters) was used during the emulation process, as shown in Figs. 6 and 7.

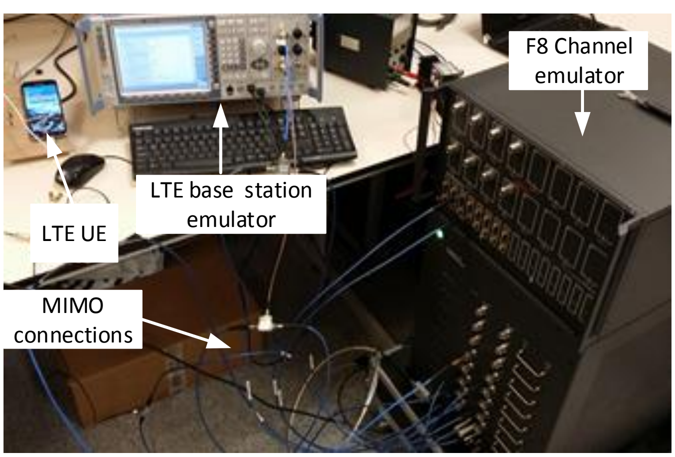

Fig. 6. Conductive LTE-A laboratory configuration for testing on-car data modems and antenna systems.

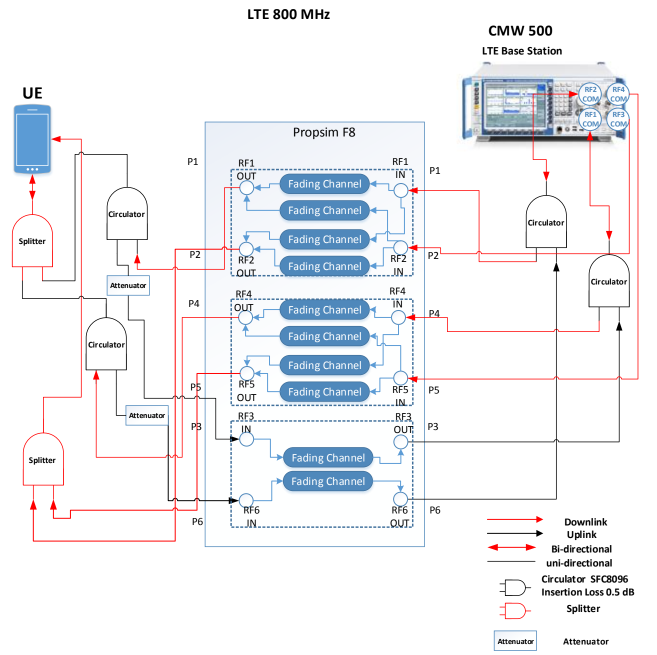

Fig. 7. MIMO LTE laboratory configuration for dual LTE-A BS emulation.

B. Description of the Drive Test Scenario

A 2.7 km test route was defined in the city scale ray tracing model to generate the channel data (based on the ten strongest multipath) necessary to perform the hardware-in-the-loop virtual drive test. Importantly, the same route was also used to capture LTE-A validation data in the physical world. The drive test provides a representative route connecting two major points of interest in the center of Bristol. In total, 1809 ray tracing location points were chosen along the route, with the exact co-ordinates based on the vehicular Global Positioning System (GPS) logs from the real-world tests performed by Jaguar Land Rover (JLR). The spacing between contiguous spatial locations in the model was approximately 1.5m. Two LTE-A BS covered the selected test route. This was arranged in order to analyze and ensure successful laboratory emulation of the BS handover process. Handover was also considered (offline as a channel modeling pre-processing stage) between adjacent BS sectors at each site. Figs. 8(a) and 8(b) illustrate a section of the selected route, which passes alongside the river from right to left.

Based on analysis of the measurement data, there were three sector handovers for BS 1, which occurred in the right-hand region of Fig. 8(a). There were no sector handovers for BS 2 (located in the left-hand region of Fig. 8(a)). Due to legal limitations, we are unable to report the exact location of the BS 1 and BS 2. The handover from BS 1 to BS 2 occurred in the marked elliptical region shown in Fig. 8(a). Figure 8(b) shows a view of the road for a segment of the test route.

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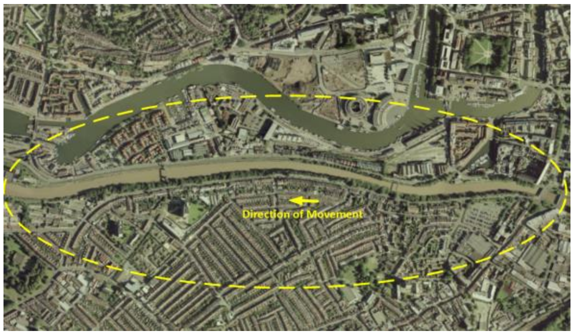


(a)

(b)

Fig. 8. (a) Bristol Test route and BS handover region and (b) view of test road segment.

A summary of the settings used in the urban test-case scenario is given in Table I. The assumed BS transmit power was calibrated based on the ray tracing results and the logged data from the real-world vehicular measurement reports.

Next, we analyze the VDT method alongside the physical drive test data obtained for the urban route shown in Fig. 8. A comparison between the predicted RF power at the OBU, the VDT emulation output (data throughput) and the validation measurement data is provided for the vehicular test route. The study was based on an 800MHz LTE-A connection to the vehicle, and includes handover analysis from BS 1 to BS 2. Laboratory based HIL measurements were performed using the previously defined VDT system to determine the radio channel dependent link quality metrics, such as Reference Signal Received Power (RSRP) and Physical Downlink Shared Channel (PDSCH) throughput.

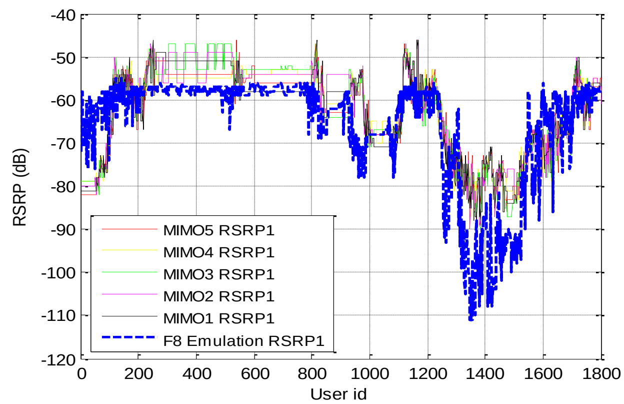
TABLE I. LTE TEST-SCENARIO SETTINGS

Environment Type	Urban (Bristol city-center)
Vehicle Route Length	2.7 km
Number of ray-tracing points	1809
Frequency of Operation	806 MHz (LTE band 20)
Channel Bandwidth	10MHz
BS antenna type	Panel Antenna (16 dBi gain)
Vehicle antennas	MIMO1 (6 dBi)
	MIMO2 (8 dBi)
OBU Receive Sensitivity	-95 dBm
Transmit Power	34 dBm

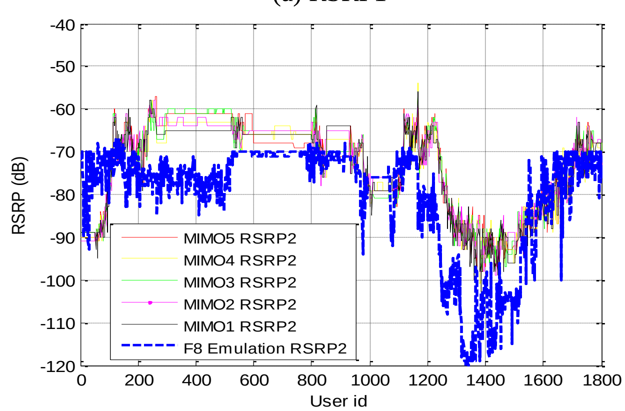
The same radio channel dependent link quality metrics were also logged in the physical drive tests, which were performed many times at different times and days of the week. This ensured sufficient data to study measurement variability and to perform the VDT comparative analysis.

V. MIMO PERFORMANCE EVALUATION ANALYSIS

The RSRP results for MIMO antennas (RSRP1 and RSRP2) from five repeated drive test measurements and emulations are presented respectively in Fig. 9. The *x*-axis shows the user id, which is an incremental indication of vehicular location along the test route. The RSRP value in the emulation was capped at -60dBm because of the input power limitations of the F8 (0dBm). However, this does not affect accuracy since the maximum signal-to-interference-plus-noise ratio (SINR) is capped at 30dB by the mobile phone. RSRP variations due to varying traffic conditions were observed between the five repeated drive tests.



(a) RSRP1



(b) RSRP2

Fig. 9. RSRP Emulation data compared with measurements.

Fig. 9 shows that better alignment between the predictions and measurements was achieved for RSRP1, since the transmit power was calibrated for the primary antenna at the OBU. The user ids (i.e., vehicle sample locations) are based on the GPS log for 1809 data samples. Handover was triggered based on OBU measured RSRP values, indicating that the handover occurs in the region around user id 1400.

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Fig. 10 presents the captured drive test throughput values for five drive tests taken over the same route at different times and days of the week. This allowed us to understand the level of variability seen in the real world over the same measurement route. In Fig. 11 the variability of the individual emulation tests (throughput) is illustrated. We see the variability associated with the VDT process is less than that observed in the real world. Performance comparison between captured drive test and emulated data throughputs versus distance is performed on the basis of the exact same route.

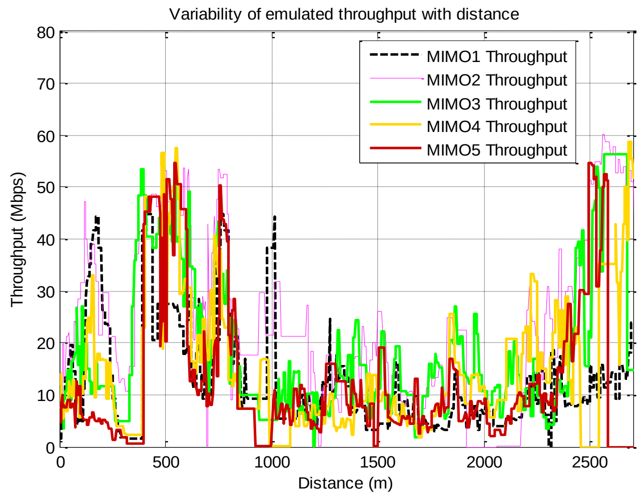


Fig. 10. Measurement Throughput data for different real-world drive tests.

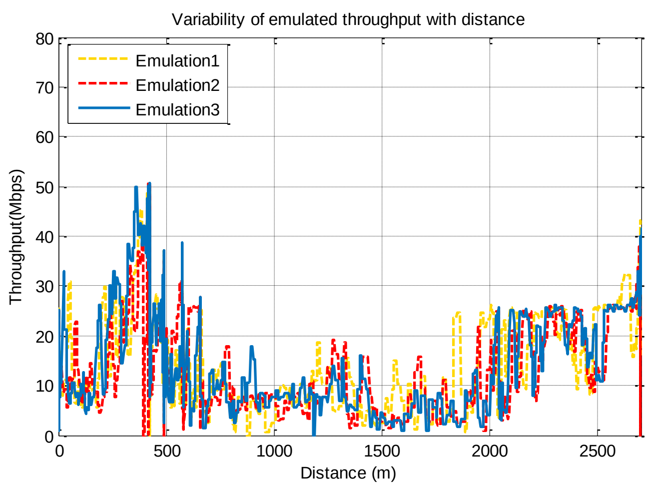
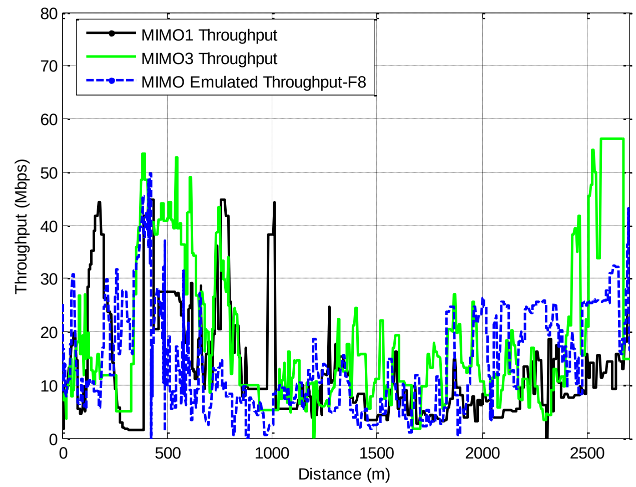


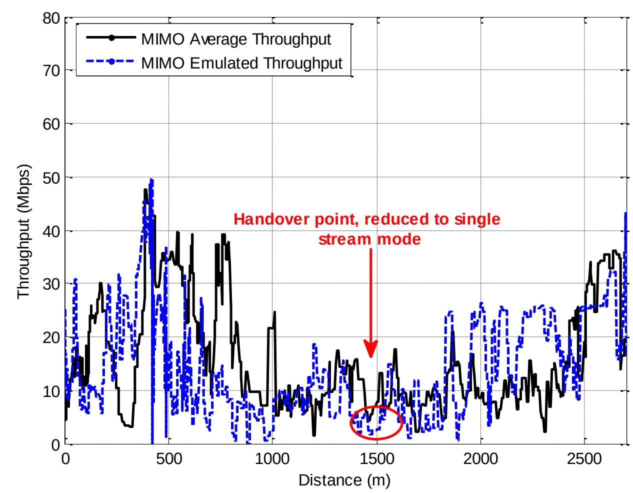
Fig. 11. Emulated Throughput data for different virtual drive tests.

During the drive tests higher throughput values (50-60 Mbps) are depicted at 500-600m and 2500m into the test route (close to a serving BS), whereas minimum throughput values (5-10 Mbps) are observed close to the handover zone (1500-1600m). In terms of the emulated data throughputs depicted in Fig. 11, as mentioned previously, lower variability is achieved between different emulated runs over the same route. It is clear that the emulator represents a more reliable, stable and repeatable process for determining data throughput for a given OBU and vehicular antenna system compared to real-world drive tests. This is a key benefit of VDT and justifies the use of emulation in the assessment of future vehicular communication systems.

Fig. 12(a) provides a comparison between the emulated results and two of the measurement runs. Fig. 12(b) also compares against the average of these two real-world measurement runs.



(a)



(b)

Fig. 12. MIMO Throughput measurements of MIMO1 and MIMO3 compared with MIMO emulated throughput rates.

We observe that the emulation results follow the measurement trends very well. Without prior knowledge, it is not possible to determine which results were real and which were generated via VDT. It should be noted that throughput depends strongly on the channel conditions, the OBU antenna system (including mounting location), radio resource allocation and the link adaptation algorithm deployed at the BS. Results also depend on the stability of the logging software. As a result, different throughput results can be observed for the same route in the real-world drive tests, causing results to vary significantly between different runs (Fig. 10). MIMO throughput emulation results showed a maximum throughput of around 50Mbps. As seen in the measurements, a reduction of throughput was observed prior to the BS handover point (1450m into the test route).

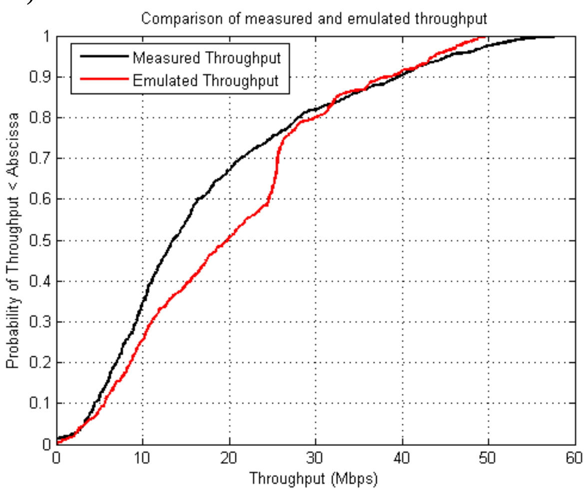


Fig. 13. CDF comparison of measured and emulated throughput

Fig. 13 presents a comparison of the Cumulative Distribution Function (CDF) of the measured and emulated throughput. It is apparent that the suggested VDT agrees well with the measured data from the same test route.

VI. CONCLUSIONS

This paper describes a new general antenna test and radio performance analysis process by using conductive RF testing and antenna/channel emulation to perform laboratory based virtual drive tests for V2I applications based on LTE-A. The test procedure was described in detail and numeric comparisons were reported with real-world measurements for a 2.7 km vehicular LTE-A test route. More specifically, 3D geographic digital maps for Bristol and measured/simulated antenna patterns have been incorporated into a 3D ray-tracing engine to generate the site-specific electromagnetic channel data required to drive the emulation process. This technique offers a pragmatic channel modeling approach since the wireless MIMO channel matrices are generated based on representative urban environments. This also allows different OBU antenna systems and vehicular mounting positions to be assessed.

The analysis considered link quality metrics such as RSRP and PDSCH throughput. The emulated results showed that in most cases the downlink speeds vary between 10-40 Mbps, with the maximum throughput being 50 Mbps. As expected, a reduction in throughput was observed in the vicinity of the handover zone. Interestingly, the road drive test throughputs for the same route were seen to vary in most cases between 10-50 Mbps. The downlink throughput performance of the Virtual Drive Tests with the LTE-A client using link adaptation showed a remarkable level of agreement with the drive tests.

The propagation prediction process has been validated against real-world drive test measurements (independently performed by Jaguar Land Rover) with very good agreement reported. The accuracy of the emulated throughputs was shown to agree well with independent real-world measurements for MIMO operation. VDT results were shown to be more reliable and repeatable than real-world drive tests. Using this high-fidelity approach, we were able to simulate the real-world radio channels experienced by a vehicular LTE-A user. VDT is able to provide automotive manufacturers with a powerful and cost-effective alternative to on-road testing. The use of city wide geographic databases allows a wide range of operating environments to be considered, including rural as well as urban routes.

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REFERENCES

[1] X. Hu, H. Wang, X. Tang, “Cyber-Physical Control for Energy-Saving Vehicle Following with Connectivity”, *IEEE Transactions on Industrial Electronics*, vol. 64, no.11, pp. 8578 – 8587, 2017.

[2] J. B. Kenney, “Dedicated Short-Range Communications (DSRC) Standards in the United States”, *Proceedings of the IEEE*, vol. 99, no. 7, pp. 1162 – 1182, 2011.

[3] *IEEE Standard for Information Technology Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks Specific Requirements; Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications; Amendment 6: Wireless Access in Vehicular Environments*, IEEE Std. 802.11p, Jul. 2010.

[4] H. Seo, K. Lee, S. Yasukawa, Y. Peng, and P. Sartori., “LTE Evolution for Vehicle-to-Everything (V2X) Services,” *IEEE Communication Magazine*, vol. 54, no. 6, pp. 22–28. Jun. 2016.

[5] J. Choi et al, “Millimeter-Wave Vehicular Communication to Support Massive Automotive Sensing*”, IEEE Communications Magazine*, vol. 54, no. 12, pp. 160 – 167, 2016.

[6] G. Remy et al, “LTE4V2X: LTE for a centralized VANET organization”, *IEEE Global Telecommunications Conference (GLOBECOM)*, 2011.

[7] Y. Tseng, "LTE-Advanced enhancement for vehicular communication", *IEEE Wireless Communications*, vol. 22, no. 6, pp. 4 -7, 2015.

[8] G. Karagiannis, A. Onur, E. Eylem, H. Geert, J. Boangoat, L. Kenneth, and T. Weil, “Vehicular networking: A survey and tutorial on requirements, architectures, challenges, standards and solutions,” *IEEE Communications Surveys & Tutorials* 13, no. 4, pp. 584-616, 2011.

[9] C. Sturm and W. Wiesbeck, “Ray-tracing in a Virtual Drive for mobile communications,” *2009 3rd European Conference on Antennas and Propagation*, pp. 1937-1939, 2009.

[10] L. Reichardt, J. Maurer, T. Fugen and T. Zwick, “Virtual Drive: A Complete V2X Communication and Radar System Simulator for Optimization of Multiple Antenna Systems,” *Proceedings of the IEEE*, vol. 99, pp. 1295-1310, 2011.

[11] FEKO. (2017, Oct.). *WinProp, Drive Test Emulator*. [Online]. Available: https://altairhyperworks.com/product/FEKO/WinProp---ProMan-Test-Drives

[12] Anite. (2017, Oct.). *Virtual Drive Testing Toolset* [Online]. Available: http://literature.cdn.keysight.com/litweb/pdf/5992-1598EN.pdf?id=275-4084

[13] E. Org. (2011, Dec.). *Field-to-Lab Infuses the Real World Into Mobile-Device Virtual Testing* [Online]. Available: http://mobiledev-design.com/learning-resources/field-lab-infuses-real-worldmobile-devic-e-virtual-testing-0

[14] Spirent. (2017, Oct.). *Spirent Virtual Drive Test (VDT)-Conversion Tool* [Online]. Available: https://www.spirent.com/Products/Virtual_Drive_T-esting

[15] S. Alaa El Din, A. Roy and F. Klinkenberg, “Mobile Online Connectivity Test Centre In-Lab Emulation Of Real-Word Connectivity Environment

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For Virtual Drive Test", *Simulation and Testing for Vehicle Technology: 7th Conference*, Berlin, May 2016.

[16] W. Fan, I. Carton, P. Kyösti and G. Frølund Pedersen, "Emulating Ray-Tracing Channels in Multi-Probe Anechoic Chamber Setups for Virtual Drive Testing," *IEEE Transactions on Antennas and Propagation*, vol. 64, pp. 730 -739, 2016.

[17] P. Lal Shrestha, M. Hempel, P. Mahasukhon, T. Ma and H. Sharif, "Quantitative performance analysis of 3.65 GHz mobile WiMAX," *IEEE Consumer Communications and Networking Conference (CCNC)*, pp. 687–689, 2012.

[18] E.K. Tameh and A.R. Nix, "The use of measurement data to analyze the performance of rooftop diffraction and foliage loss algorithms in a 3-D integrated urban/rural propagation model," *IEEE 48th Vehicular Technology Conference (VTC-Spring)*, May 1998.

[19] W. Zhenyu, E. Tameh and A. Nix, "Joint Shadowing Process in Urban Peer-to-Peer Radio Channels," *IEEE Transactions on Vehicular Technology*, vol. 57, no. 1, pp. 52-64, Jan. 2008.

[20] E.K. Tameh and A.R. Nix, "A 3-D integrated macro and microcellular propagation model, based on the use of photogrammetric terrain and building data," *IEEE 47th Vehicular Technology Conference*, 1997.

[21] Y.Q. Bian, A.R. Nix, E.K. Tameh and J.P. McGeehan, "MIMO–OFDM WLAN Architectures, Area Coverage, and Link Adaptation for Urban Hotspots", *IEEE. Transactions on Vehicular Communications*, vol. 57, no. 4, 2008.

[22] M. Steinbauer, A. Molisch and E. Bonek, "The double-directional radio channel," *IEEE Antennas and Propagation Magazine*, vol. 43, no. 4, pp. 51-63, Aug. 2001.

[23] T. Thomas, F. Vook, E. Visotsky, E. Mellios, G. Hilton and A. Nix, "3D extension of the 3GPP/ITU channel model," *Proceedings of IEEE 77th Vehicular Technologies Conference (VTC-Spring)*, Dresden, Germany, Jun. 2013.

[24] E. Mellios et al, "Impact of Low-Frequency Radar Interference on Digital Terrestrial Television", *IEEE Transactions on Broadcasting*, vol. 59, no. 1, Mar. 2013.

[25] E. Mellios, A. Nix and G. Hilton, "Ray-tracing urban macrocell propagation statistics and comparison with WINNER II/+ measurements and models," *8th Loughborough Antennas and Propagation Conference (LAPC)*, Loughborough, UK, Nov. 2012.

[26] T. Haagenson et al, "Textile Antennas for Spacesuit Applications: Design, simulation, manufacturing, and testing of textile patch antennas for spacesuit applications," *IEEE Antennas and Propagation Magazine*, vol. 57, no. 4, pp. 64-73, 2015.

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